ISSUES ON INTERNET-BASED TELEOPERATION

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Abstract: This paper describes experiments of Internet modeling and of Internet-based teleoperation aimed at developing suitable control laws to overcome the variable time-delay and the data losses typical of Internet communication. From a control perspective, Internet is shown to be characterized by mean and jitter of the data packets delay, and by packet losses. Furthermore, these parameters depend on the number of nodes traversed by the packets and on the specific network traffic. The effects of packet delay jitter and losses on teleoperation performance are demonstrated using a 2-dof force feedback master.

Keywords: Teleoperation, bilateral force/position control, variable time-delay systems, Internet real-time communication.

1. INTRODUCTION

According to recent statistics (Wizards, 1996), Internet has reached 12 millions hosts around the world, and is rapidly approching the 100 millions mark. Moreover, its throughput is also constantly increasing to support multimedia sessions involving audio, video and textual data. Internet is fast becoming the preferred form of interactive communication, with new applications in multi-players games, teleconferencing and tele-medicine being developed and tested every day.

It will not be too long before complex robotic devices will be controlled remotely through the Internet. For example, development is under way of *service robots* that will assist health care professionals at home and in hospitals (Dario *et al.*, 1995; Fiorini *et al.*, 1997). Since these devices will interact with people and the environment, they will require new control procedures to ensure realistic and stable force feedback.

This paper addresses some of the main problems of Internet-based control systems. The model for a typical Internet connection is derived in Section 2. The critical issues of direct Internet-based control are described in Section 3, and the effects of Internet characteristics on a force-reflecting teleoperator are presented in Section 4. Then, Section 5 summarizes the paper and presents our plans for future research in this area.

2. INTERNET MODELLING

As a first approximation, Internet can be considerd as a strongly connected network of computers, communicating with each other using packet-switched protocols (Comer, 1991). The delay af-

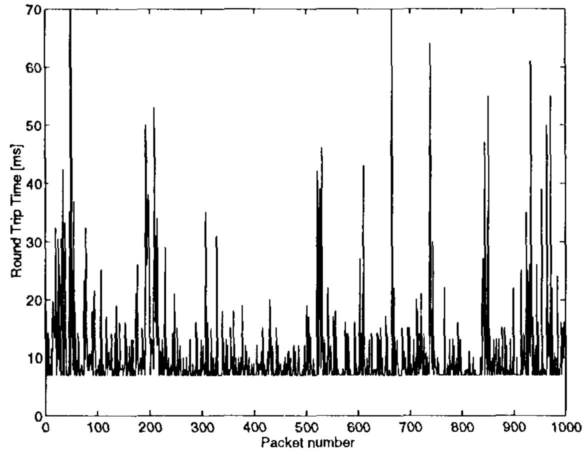

Fig. 1. Plot of round trip time for Berica

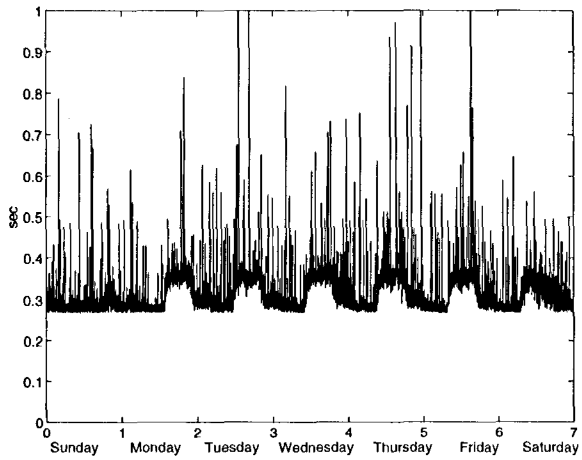

Fig. 2. Weekly variation of RTT for Helios

fecting the data packets exchanged between two computers is affected by several factors. First, packet's routes are assigned dynamically, depending on the network load. Then, packets are subject to different handling policies at each node they traverse, since nodes may have different throughput, routing policy, and buffering and queues management. Furthermore, when the number of data packets exceeds the bandwidth available, congestion occurs. Congestive behaviour can be modeled as a Markov chain whose states depend on the communication protocol (Bolot *et al.*, 1990). Thus, it is almost impossible to determine a detailed analytical model of an Internet communication.

An accepted approximate model consists of a network of queues, one for each node along the dynamic path connecting two computers (Hammond and O'Reilly, 1986). Queuing and dynamic routing introduce a variable transmission delay or jitter. A congested path results in an unpredictible deferral of the packets and their possible elimination in case of long deferrals, since packets have limited life time. Thus, the approximate Internet model is characterized by the statistics of

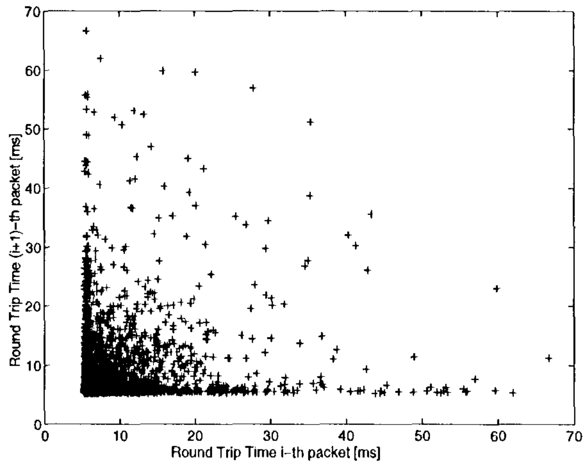

Fig. 3. Phase plot for Berica

the packet delay and of the packet losses. These parameters are usually measured in terms of the communication Round Trip Time (RTT), i.e. the time taken by a packet to reach a remote computer and return to the issuing computer. Note that simple one way measurements cannot be used, since they don't provide a sufficient resolution.

The parameter values of the Internet model are available in the literature (Bolot, 1993), however, because of the rapid Internet growth, they must be frequently updated. For this reason, experiments were carried out to measure the parameters of the connections between a local computer (Arianna) at the University of Padova, and two computers located at distances of 30 km (Berica) and 10000 km (Helios), respectively. Here, the RTT is measured using a modified *ping* procedure, consisting of an Internet Control Message Protocol (ICMP) packet of 32 bytes sent with period $\delta = 100\ ms$ using the Internet UDP protocol, whose negligible overhead allows to measure the true delay of the connection. Note that other Internet protocols, such as TCP/IP for example, are not suitable for these experiments, since their overhead includes the acknowledgement of each received packet, i.e. a packet is transmitted only after the previous packet has been acknowledged.

The parameters measured during the experiments include the number of nodes traversed and the RTT value. These parameters are displyed in the following using *time series*, *phase plots*, and *histogram* representations. The time series plot represents a finite set of of observations of a random process in which the parameter is time (Oppenheim and Shafer, 1975). The phase plot displays on the x-axis the RTT of packets n, rtt_n, and on the y-axis the RTT of packets $n+1$, rtt_{n+1}. A point is displayed in the phase plot if there is a value n such that $x = rtt_n$ and $y = rtt_{n+1}$. Finally, the histogram shows the number of packets with the same RTT. In

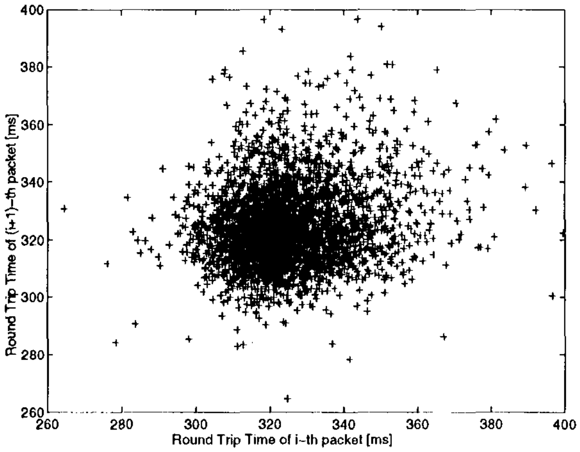

Fig. 4. Phase plot for Helios (δ=100 msec).

this discussion we follow the approach presented in (Bolot, 1993).

The number of traversed node, i.e. routing computers, increases almost linearly with distance, being equal to 5 for the connection to Berica and to 18 for Helios. However, the relation between the number of nodes and RRT is less obvious, since not all nodes introduce the same delay. The time series of Fig. 1 shows that RTT has a random component added to a constant term, which represents the minimum service time along the network. This term however, is constant only for short periods, since it is affected by daily and weekly variations, as shown in Fig. 2 for a weekly record of the connection to Helios.

The phase plot shown in Fig. 3 represents the typical distribution for a non-congested communication with Berica over a period of about 2 minutes. Here, the RTT value is equal to $rtt_{n+1} = rtt_n - \epsilon_n$, where ϵ_n is a random process with zero mean and low variance. The points in the phase plane cluster around the line $rtt_{n+1} = rtt_n$, with higher density close to the minimum delay of the channel, represented by the lower left corner of the plot with coordinates $(5, 5)$. Similarly, the plot for a non congested connection with Helios, is shown in Fig. 4. However, due to the increased distance, the clustering is no longer around the minimum value of RTT, but around its average value, at point $(326, 326)$. It is worthnoticing that this behaviour was not observed in (Bolot, 1993), since all the experiments were performed between nodes in USA. In this case, the connection is usually constituted by a couple of fairly slow connections from the terminal nodes to a high speed backbone. Then, the total delay results to be determined mainly by the sum of two large delays (relative to the slow connections), which values depend on the load of the local connection and then it usually results fairly constant. On the other hand, in case of inter-continental connections, the number of bottlenecks along the path increases. There are several connections with comparable delays, then the total delay may vary considerably around its average value. This will be confirmed in the following by the analysis of delay distributions.

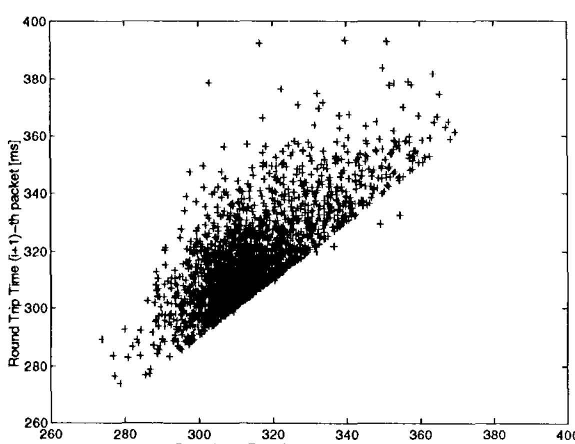

Fig. 5. Phase plot for Helios (δ=10 msec).

To show the effect of a congested channel on the phase plot, the period of the probing packet is decreased to $\delta = 10\ ms$, resulting in the plot of Fig. 5. The points are now clustered above the line

$$rtt_{n+k+1} = rtt_{n+k} + P/\mu - \delta \qquad (1)$$

where P is the packet length and μ is the channel throughput (Bolot, 1993). In this case, the channel is not completely saturated, since line (1) is below the center of the cluster, i.e. $\delta \geq P/\mu$. Figure 5 shows the effect of heavy traffic on the time delay. RTT has now a lower bound due to the actual network throughput.

The dependency of RTT on the connection length is evident from the shape of the delay distribution. The measurements for the connection with Berica have the exponential distribution shown Fig. 6, whereas the measurements with Helios have the Gaussian distribution shown in Fig. 7. These results are consistent with the phase plots of the two connections shown in Fig. 3 and 4. The distribution of Fig. 7 is explained by considering each node as a *FIFO* queue with random arrivals and exponential service time (this is known as *[M,M,1]* queue) (Hammond and O'Reilly, 1986). As the number of queues increases with the number of nodes traversed, the total delay is equal to the sum of a large number of exponentially distributed independent random variables, thus the resulting Gaussian distribution.

The data representing the packet losses characteristics for the connections with Berica and Helios are summarized in Tab. 1 for the two probing rates used. The table shows the dependence on the connection lenght and on the probing rate. This result could be expected, since higher prob-

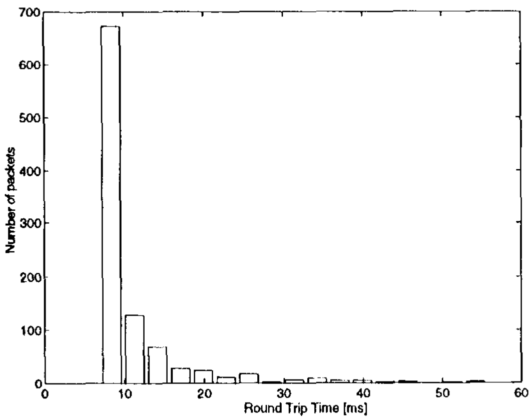

Fig. 6. RTT distribution for Berica.

Host name	δ [msec]	Average RTT [msec]	Std. Dev.	Packet loss rate
	10			
Berica		8.44	6.25	5.97
Helios		319.0	16.70	51.13
	100			
Berica		8.10	5.35	0.08
Helios		326.3	27.20	41.36

Table 1. Packet loss statistics

ing rates result in increased network load and in higher packet losses.

These experiments justify modeling Internet connections by the average value and the variance of the RTT, and provide the values of these parameters for two typical connections. Since the statistic distribution of RTT changes with the number of nodes traversed, and packet losses are due to unpredictable congestion, it is difficult to use an *a priori* model, especially for medium-distance connections. It is necessary then, to measure these parameters on-line for each specific connection.

3. INTERNET IN CLOSED-LOOP CONTROL

From the previous discussion, it follows that an Internet-based control system must deal with the time delay and the packet losses introduced by

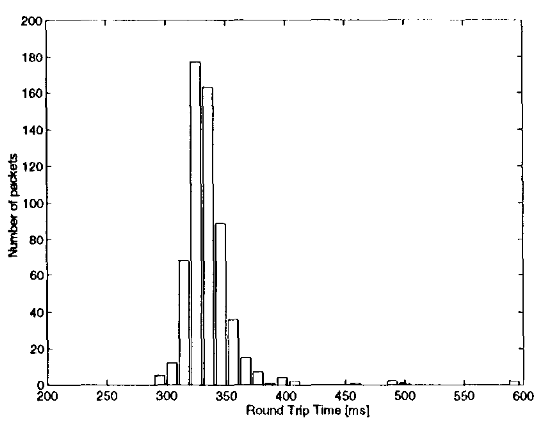

Fig. 7. RTT distribution for Helios

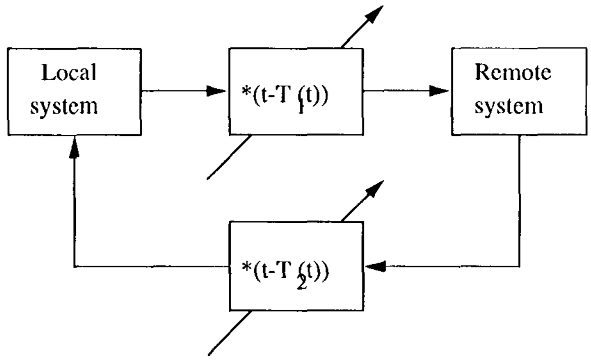

Fig. 8. Model of remotely-controlled system

the computer network. This is not a new problem, since every communication system introduces a delay in the control loop. The difficulty here is represented by the jitter of the time delay, which can be schematically represented as shown in Fig. 8. In the case of linear controller and process, this model can be simplified by combining these delays into a single delay $T(t)$ located in the forward path.

Previous work on teleoperation with time-delay has focused on constant delay systems (Anderson and Spong, 1989; Kim *et al.*, 1992; Niemeyer and Slotine, 1991). In (Eusebi and Melchiorri, 1995), it is shown that some of these methods achieve an IOD stability, i.e. *independent of delay*. Similarly, previous work on control algorithms for time-delay systems has focused on compensating delays that are either constant or known (Brierley *et al.*, 1982; Mori and Koname, 1989; Kharitonov and Zhabko, 1994; Kojima *et al.*, 1993), and therefore they are not directly applicable to Internet-based teleoperation, since Internet delays are modeled as random variables.

A simple solution to a random time-delay could be to consider its maximum, and to use it in the design of a worst-case controller. Unfortunately, it is shown in (Hirai and Satoh, 1980) that a control algorithm designed for a fixed, maximum delay T, may not stabilize the system when the delay t varies from 0 to T. So far, only few authors addressed this problem. In (Mahmoud, 1996; Wu *et al.*, 1993) it is shown that the allowable performance is limited by the upper values of the delays in the system. The problem of rapid delay jitter, and possible packet scrambling, is approached by storing the incoming packets in a memory buffer and by estimating the original data (Luck and Ray, 1994). Another technique considers the effects of the delay on a norm of the system and finds a controller whose design is independent of the delay and its variations (Matsumoto, 1995). The main performance problem is due to packet losses. In fact, even if the delay jitter can be completely compensated (e.g. with additional queues of proper lenght at both sides of the connection),

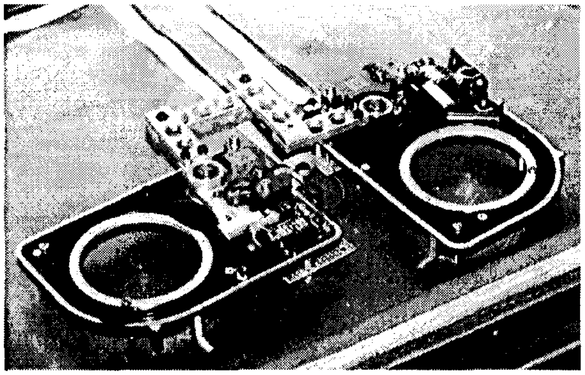

Fig. 9. Master robot of the telerobotic equipment

no remedy exists for lost data. So far, the issue of the packet losses has been addressed by showing that some packet loss can be compensated by using a n-step predictor (Luck *et al.*, 1992). However, such predictor requires the knowledge of the models of the local and remote processes, and the robustness of this approach is not clear. A less demanding approach consists of taking advantage of the availability of the statistic distribution of the losses, and of modeling the effect of the losses in terms of convergence of the overall system to the desidered working point. In summary, the design of a suitable controller for a system that integrates an Internet connection, is an open research field. So far, variable time-delays and packet losses have been considered separately and the combined effects of such Internet characteristics have not been studied yet. This will be the matter of our future research.

4. EXPERIMENTAL RESULTS

To gain some insight into the problem of Internet-based telerobotic systems, a few qualitative experiments have been carried out with a virtual telemanipulation system consisting of a 2-dof force reflecting master, and a virtual slave simulated by software.

The equipment consists of the 2-dof planar manipulator, shown in fig. 9, with a $4\,\mathrm{cm}^2$ working area, controlled by a laptop personal computer (PC) (Buttolo *et al.*, 1995). The planar manipulator is the master of the virtual telerobotic system, and it controls the position of a virtual cartesian slave simulated in software. The master is connected to the PC via a PCMCIA I/O board, also providing the system clock. The PC communicates to the Internet using a UDP-based library (Buttolo *et al.*, 1995) that satisfies the requirements for real-time Internet communication summarized in (Fiorini and Oboe, 1997).

The master's end effector position is sent through Internet to a remote host, which acts as a *reflector* by sending back the received data, as shown in fig. 10. The received data are then used as set point for the slave robot. In this application, the virtual slave has a negligeable dynamic and its end effector is defined as an object in the virtual environment. Each virtual object can be defined in both its geometric (shape, dimension, initial position) and mechanical (mass, stiffness, friction, etc.) properties. From the interaction of the virtual end effector with all the other objects that the user places in the virtual environment, the force feedback is obtained. This is then applied to the master robot by commanding the corresponding currents into the motors.

Several experiments were carreid out with this sytem to study the effects of delays and packet losses. We report here a few qualitative results with two different connections: a local one, with less than 1 ms RTT, and a second one with an average RTT of 300 ms. All the experiments are performed using a loop rate of 10 ms.

First, we compared the force reaction obtained at the master's side when the user pushes the virtual slave robot against a soft wall. Fig. 11 shows no noticeable delay or distortion introduced by a local Internet connection. This results in a smooth contact with the soft object and a controllable interaction force. Fig. 12 shows the effects of the remote connection.

In this case, in addition to the 300 ms delay, we observe some distortion in the received data, due to delay jitter and losses (in this connection, around 3 %). The resulting force feedback is less smooth than with the local connection, with several peaks due to the effects of both the operator dynamics (that tends to destabilize the system) and the packet losses.

The qualitative effects of Internet on the haptic performance of the system are shown in Fig. 13, represeting a user tracking the smooth profile of a corner of a virtual object. The local connection enables a smooth tracking, whereas the remote connection shows some unstability due to the delay (this can be observed as a waveing motion) and some roughness due to the packet losses (in form of spikes on the trajectory).

The results obtained with force-feedback teleoperator with the virtual slave and workspace con-

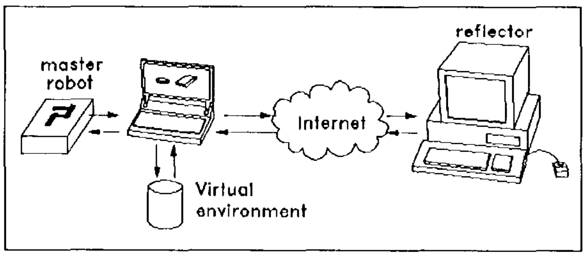

Fig. 10. Internet-connected telerobotic equipment

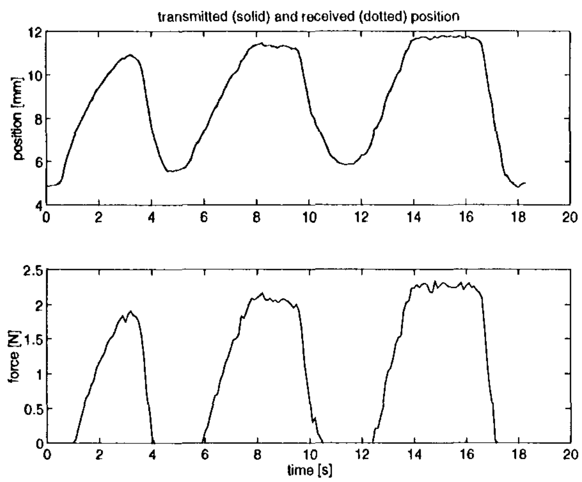

Fig. 11. Soft wall contact - local connection

firm that unstability appears in presence of large communication delays. As for the haptic performance, this is affected also by the packet losses, as they result in spikes in the force applied to the master and then in an additional roughness in the rendered surfaces. The haptic performance is also influenced by the characteristics of the contact between the slave's end effector and the objects. With the virtual environment at the slave side, it is possible to set up several experiments in order to study such influence.

5. CONCLUSIONS

This paper describes some of the issues relevant to the use of Internet within a control system, and reports on experiments of Internet modeling and of Internet-based teleoperation. The experiments highlight the main characteristics of Internet, and the effects on the performance of a teleoperation system. The design of a suitable control law for Internet based control systems requires the integration of specific techniques for handling the problems of delay jitter and data losses. However in a non-congested network, the experiments show that Internet holds interesting promises. It is worthwhile to investigate this problem further, to identify control laws capable of fully exploiting Internet potential, and to develop formal methods to evaluate its overall performance.

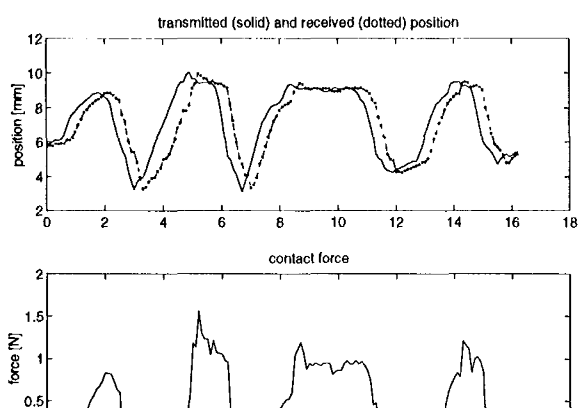

Fig. 12. Soft wall contact - remote connection

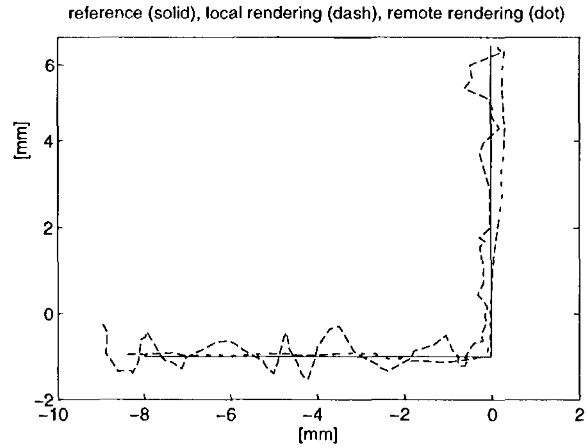

Fig. 13. Comparison between local and remote surface tracking

6. ACKNOWLEDGMENT

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